

Accepted to the Astrophysical Journal

The Radio Evolution of SN 2001gd

Christopher J. Stockdale

*Marquette University, Physics Department, PO Box 1881, Milwaukee, WI, 53214-1881,
christopher.stockdale@mu.edu*

Christopher L. Williams¹

Naval Research Laboratory, Code 7213, Washington, DC 20375-5351, clmw@mit.edu

Kurt W. Weiler

*Naval Research Laboratory, Code 7210, Washington, DC 20375-5320,
kurt.weiler@nrl.navy.mil*

Nino Panagia^{2,3}

*Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218,
panagia@stsci.edu*

Richard A. Sramek

*National Radio Astronomy Observatory, P.O. Box 0, Socorro, NM 87801,
dsramek@nrao.edu*

Schuyler D. Van Dyk

IPAC/Caltech, Mail Code 100-22, Pasadena, CA 91125, vandyk@ipac.caltech.edu

and

Matthew T. Kelley

*Marquette University, Physics Department, PO Box 1881, Milwaukee, WI, 53214-1881,
matthew.kelley@mu.edu*

¹Present address: Massachusetts Institute of Technology, Kavli Institute for Astrophysics and Space Research, Cambridge, MA 02139

²INAF-Osservatorio Astrofisico di Catania, Via S. Sofia 78, I-95128 Catania, Italy

³Supernova Ltd., Olde Yard Village #131, Northsound Road, Virgin Gorda, British Virgin Islands.

ABSTRACT

We present the results of observations of the radio emission from Supernova 2001gd in NGC5033 from 2002 February 8 through 2006 September 25. The data were obtained using the Very Large Array at wavelengths of 1.3 cm (22.4 GHz), 2 cm (14.9 GHz), 3.6 cm (8.4 GHz), 6 cm (4.9 GHz), and 20 cm (1.5 GHz), with one upper limit at 90 cm (0.3 GHz). In addition, one detection has been provided by the Giant Metrewave Radio Telescope at 21 cm (1.4 GHz). SN 2001gd was discovered in the optical well past maximum light, so that it was not possible to obtain many of the early radio “turn-on” measurements which are important for estimating the local circumstellar medium (CSM) properties. Only at 20 cm were turn-on data available. However, our analysis and fitting of the radio light curves, and the assumption that the Type IIb SN 2001gd resembles the much better studied Type IIb SN 1993J, enables us to describe the radio evolution as being very regular through day ~ 550 and consistent with a nonthermal-emitting model with a thermal absorbing CSM. The presence of synchrotron-self absorption (SSA) at early times is implied by the data, but determination of the exact relationship between the SSA component from the emitting region and the free-free absorption component from the CSM is not possible as there are insufficient early measurements to distinguish between models. After day ~ 550 , the radio emission exhibits a dramatically steeper decline rate which, assuming similarity to SN 1993J, can be described as an exponential decrease with an e-folding time of 500 days. We interpret this abrupt change in the radio flux density decline rate as implying a transition of the shock front into a more tenuous region of circumstellar material. A similar change in radio evolution has been seen earlier in other SNe such as SN 1988Z, SN 1980K, and SN 1993J.

Subject headings: supernovae, individual (SN 2001gd), galaxies, individual (NGC5033), radio continuum, stellar evolution: massive stars

1. Introduction

Supernova (SN) 2001gd was discovered at magnitude 16.5 on 2001 November 24.820 UT by Nakano *et al.* (2001), located $\sim 3'$ north-northwest of the center of NGC 5033. Nakano *et al.* (2001) report a position of $\alpha = 13^h 13^m 23^s.89$, $\delta = +36^\circ 38' 17''.7$ (J2000), for the SN and note that nothing was detected at this position in previous CCD images taken 179 days earlier (2001 May 29) to a limiting magnitude of 19. Ten days later, Matheson *et al.*

(2001) obtained a spectrum of the SN, identifying it as a Type IIb SN well past its maximum light, with weak helium lines and nebular-phase lines of magnesium, oxygen, and calcium beginning to dominate. They noted that this spectrum was nearly identical to that of Type IIb SN 1993J, on day 93 after its explosion. Using this suggestion to constrain the explosion date for the SN, we assume that the optical discovery occurred ~ 83 days after the explosion and, therefore, for calculating the age of the supernova we assume an explosion date of 2001 September 03, which is the same explosion date assumed by Pérez-Torres *et al.* (2005).

Tully (1988) gives the distance to NGC 5033, as 18.7 Mpc (calculated with $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$). Accepting their distance calculation and correcting it with an updated value of the Hubble constant $H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$ gives a distance to the SN of ~ 21.6 Mpc. We note, however, that NGC 5033 is the host of several historical supernovae, including the radio emitting SN 1985L (Van Dyk *et al.* 1998). If we follow Van Dyk *et al.* (1998) and estimate the Tully (1988) distance with Hubble constant $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, we obtain a distance to NGC 5033 of ~ 20 Mpc. Since a change in the distance estimate of $< 10\%$ will not significantly affect any of our estimates of the SN physical properties, we will, for consistency with the previous radio work, use in this paper the Van Dyk distance of 20 Mpc. However, it should be noted that Pérez-Torres *et al.* (2005) assumed a much shorter distance of 13.1 Mpc.

SN 2001gd was first detected at radio wavelengths on 2002 February 8.54 by Stockdale *et al.* (2002), using the Very Large Array (VLA)¹ at 1.3 cm (22.4 GHz), 3.6 cm (8.4 GHz), 6 cm (4.9 GHz), and 20 cm (1.5 GHz). They report a radio position of $\alpha = 13^h 13^m 23^s 889$, $\delta = +36^\circ 38' 18'' 14$ (J2000) with uncertainties of $\pm 0''.2$ in each coordinate, which agrees with the reported optical position of Nakano *et al.* (2001) to within the errors.

Stockdale *et al.* (2003) presented the results of initial radio monitoring of SN 2001gd between 2002 February 8 and 2002 October 28. Their results showed that the radio emission evolves very smoothly, consistent with the nonthermal-emitting, thermal-absorbing model described by Weiler *et al.* (2002). Their results also indicate a CSM with significant structure embedded in a uniform medium, similar to that proposed for Type IIb SN 1993J (Van Dyk *et al.* 1994; Weiler *et al.* 2007). The similar optical spectra and early radio evolution of both SN 1993J and SN 2001gd indicate that the two Type IIb SNe may have a number of similarities.

Pérez-Torres *et al.* (2005) conducted VLBI observations of SN 2001gd at 3.6 cm (8.4 GHz) on 2002 June 26 and 2003 April 8. Although they were unable to resolve any structure

¹The VLA telescope of the National Radio Astronomy Observatory is operated by Associated Universities, Inc. under a cooperative agreement with the National Science Foundation

in the SN, they were able to estimate the SN angular size through interferometer visibility fitting and found that their data suggested a possible deceleration in the expansion (although their data were not conclusive). Using our assumed distance of 20 Mpc to the host galaxy, and the angular size limits estimated by Pérez-Torres *et al.* (2005), the upper limit to the expansion velocity of the blastwave is $\lesssim 22,000 \text{ km s}^{-1}$ for the 2002 June 26 VLBI observation (day 296). Depending on the exact nature of the emitting region, the upper limit may be as low as $\lesssim 19,000 \text{ km s}^{-1}$. Thus, for the purposes of this paper, and for comparison with SN 1993J, we assume an expansion velocity of $15,000 \text{ km s}^{-1}$.

Pérez-Torres *et al.* (2005) conducted multifrequency radio observations with the VLA on 2003 April 8 to complement their VLBI data, obtaining a spectrum consistent with synchrotron emission partially suppressed by free-free absorption. They also obtained X-ray data on SN 2001gd from XMM-Newton observations of NGC5033 on 2001 July 2 and 2002 December 18 and report the detection of X-ray emission on the latter date consistent with the expected reverse shock emission from typical Type II SNe.

Recent VLA observations indicate a dramatic change in the evolution of the radio emission from SN 2001gd. These new observations and their implications are presented in this paper.

2. Radio Observations

New radio observations of SN 2001gd have been made with the VLA at 1.3 cm (22.4 GHz), 2 cm (14.9 GHz), 3.6 cm (8.4 GHz), 6 cm (4.9 GHz), and 20 cm (1.5 GHz), with one upper limit at 90 cm (0.3 GHz) from 2002 November 08 through 2006 September 25 and are presented in Table 1 and Figure 1. For completeness and ease of reference, we include the previously published results from Stockdale *et al.* (2003), and Pérez-Torres *et al.* (2005), as well as one measurement from the GMRT (Chandra *et al.* 2002), in both Table 1 and Figure 1.

The techniques of observation, editing, calibration, and error estimation are described in previous publications on the radio emission from SNe (see, *e.g.*, Weiler *et al.* 1986, 2002; Sramek & Weiler 2003). We used 3C286 as the primary calibrator for flux density bootstrapping, while J1310+323, with a defined position of $\alpha = 13^{\text{h}}10^{\text{m}}28^{\text{s}}.66$, $\delta = +32^{\circ}20'43''.8$ served as the phase calibrator and secondary flux density calibrator. The flux densities of J1310+323 are shown in Table 2 and plotted in Figure 2. Like most phase calibrators, J1310+323 shows some variation in its flux density because phase calibrators are selected for their proximity to the SN and unresolvable angular size rather than their flux stability. The

primary calibrator is therefore used to determine the absolute flux density of the secondary calibrator at each epoch of the observations.

The listed flux density measurement errors are determined based on both the intrinsic RMS background noise level of the particular radio map, and a fractional error, ϵ , proportional to the SN flux. The RMS map noise results from both small unresolved fluctuations in the background emission and random map fluctuations due to receiver noise, while the fractional error, ϵ , accounts for the inaccuracy of VLA flux density calibration (see, *e.g.*, Weiler *et al.* 1986) and possible deviations of the primary calibrator from an absolute flux density scale. The final errors (σ_f) given for the measurements of SN 2001gd are taken as the addition in quadrature of these components:

$$\sigma_f^2 = (\epsilon S_0)^2 + \sigma_0^2 \quad (1)$$

where S_0 is the measured flux density, σ_0 is the map RMS background noise for each observation, and $\epsilon = 0.15$ for 90 cm, $\epsilon = 0.1$ for 20 cm, $\epsilon = 0.05$ for 6 cm and 3.6 cm, $\epsilon = 0.075$ for 2 cm, and $\epsilon = 0.1$ for 1.3 cm.

3. Parameterized Radio Light Curves

From the most recent RSN modeling discussion of Weiler *et al.* (2002) and Sramek & Weiler (2003), we use a parameterized model :

$$S(\text{mJy}) = K_1 \left(\frac{\nu}{5 \text{ GHz}} \right)^\alpha \left(\frac{t - t_0}{1 \text{ day}} \right)^\beta e^{-\tau_{\text{external}}} \left(\frac{1 - e^{-\tau_{\text{CSMclumps}}}}{\tau_{\text{CSMclumps}}} \right) \left(\frac{1 - e^{-\tau_{\text{internal}}}}{\tau_{\text{internal}}} \right) \quad (2)$$

with

$$\tau_{\text{external}} = \tau_{\text{CSMhomogeneous}} + \tau_{\text{distant}}, \quad (3)$$

where

$$\tau_{\text{CSMhomogeneous}} = K_2 \left(\frac{\nu}{5 \text{ GHz}} \right)^{-2.1} \left(\frac{t - t_0}{1 \text{ day}} \right)^\delta \quad (4)$$

$$\tau_{\text{distant}} = K_4 \left(\frac{\nu}{5 \text{ GHz}} \right)^{-2.1} \quad (5)$$

and

$$\tau_{\text{CSM}_{\text{clumps}}} = K_3 \left(\frac{\nu}{5 \text{ GHz}} \right)^{-2.1} \left(\frac{t - t_0}{1 \text{ day}} \right)^{\delta'} \quad (6)$$

with K_1 , K_2 , K_3 , and K_4 determined from fits to the data and corresponding to the flux density (K_1), homogeneous (K_2 , K_4), and clumpy or filamentary (K_3) free-free absorption (FFA) at 5 GHz, formally but not necessarily physically, one day after the explosion date t_0 . For a more detailed explanation of the physical meaning of the parameters, the reader should consult the references cited above.

Since it is physically realistic and may be needed in some RSNe where radio observations have been obtained at early times and high frequencies, Equation (2) also includes the possibility for an internal absorption term. This internal absorption (τ_{internal}) term may consist of two parts – synchrotron self-absorption (SSA; $\tau_{\text{internal}_{\text{SSA}}}$), and mixed, thermal FFA/non-thermal emission ($\tau_{\text{internal}_{\text{FFA}}}$).

$$\tau_{\text{internal}} = \tau_{\text{internal}_{\text{SSA}}} + \tau_{\text{internal}_{\text{FFA}}} \quad (7)$$

$$\tau_{\text{internal}_{\text{SSA}}} = K_5 \left(\frac{\nu}{5 \text{ GHz}} \right)^{\alpha-2.5} \left(\frac{t - t_0}{1 \text{ day}} \right)^{\delta''} \quad (8)$$

$$\tau_{\text{internal}_{\text{FFA}}} = K_6 \left(\frac{\nu}{5 \text{ GHz}} \right)^{-2.1} \left(\frac{t - t_0}{1 \text{ day}} \right)^{\delta'''} \quad (9)$$

with K_5 corresponding to the internal, non-thermal ($\nu^{\alpha-2.5}$) SSA and K_6 corresponding to the internal thermal ($\nu^{-2.1}$) free-free absorption mixed with non-thermal emission, at 5 GHz, formally but not necessarily physically, one day after the explosion date t_0 . The parameters δ'' and δ''' describe the time dependence of the optical depths for the SSA and FFA internal absorption components, respectively.

Application of this basic parameterization has been shown to be effective in describing the physical characteristics of the presupernova system, its CSM, and its final stages of evolution before explosion for objects ranging from the two decades of monitoring the complex radio emission from SN 1979C (Montes *et al.* 2000) through the unusual SN 1998bw (GRB980425) (Weiler, Panagia, & Montes 2001) to the very well studied SN 1993J (Weiler *et al.* 2007).

4. Radio Light Curve Description

The multi-frequency radio data for SN 2001gd are listed in Table 1 and displayed in Figure 1. Examination of the data indicates that radio evolution of the SN is best described by two distinct time intervals: an “early” interval before day ~ 550 and a “late” interval thereafter. Although the precise date of the observed “break” is not well defined, it appears that around the time of the observations of Pérez-Torres *et al.* (2005) on 2003 April 8 (day 582) the rate of flux decline markedly steepened such that the data can no longer be adequately described by the model appropriate for earlier times. Similar “breaks” have been observed in the radio light curves of other RSNe, including SN 1988Z (Williams *et al.* 2002), SN 1980K (Montes *et al.* 1998), and SN 1993J (Weiler *et al.* 2007).

An extensive search for the best parameter fits to equations (2)-(9) was carried out on the “early” interval (day < 550) by minimizing the reduced χ^2 (χ_{red}^2). Since there are only four radio detections after the measurements on day 582, the “late” radio light curve behavior is very poorly defined except to note that the few detections and the several upper limits indicate that the decline rate has significantly steepened and, following the example of SN 1993J (Weiler *et al.* 2007), are consistent with an exponential decline with an e-folding time of 500 days.

The early epoch fitting parameters are consistent with a homogeneous (K_2) CSM, although more complex structures such a CSM containing filamentary (K_3) components cannot be ruled out. No evidence is seen for any distant, homogeneous thermal absorption ($K_4 = 0$), and the very early data (< 100 days) are too sparse to determine from the fitting if SSA (K_5), or mixed, internal, free-free absorption/nonthermal emission (K_6) may have been present.

However, we have estimated the brightness temperatures for the “early” (before day ~ 550) 20 cm emission based on a pure FFA model and found that they exceed the limiting temperature for synchrotron emission of $\sim 10^{11.5}$ K calculated by Readhead (1994), which was also the case for SN 1993J (Weiler *et al.* 2007). Given our inability to model this early absorption based purely on our sparse “early” data, we have chosen to assume that SN 2001gd has a similar brightness temperature evolution ($\sim 10^{11}$ K at peak) for the 20 cm emission as it becomes optically thin. Given that SN 2001gd and SN 1993J have similar characteristics at “early” times, we estimate, as was the case for SN 1993J, that a significant SSA component is required for SN 2001gd along with the FFA component determined from fitting which describes the rapid rise of the 20 cm data well. The best parameters which we can estimate for the “early” epoch of SN 2001gd with these assumptions are given in Table 3. We note an apparent similarity between the δ and δ'' terms from our modeling of the SN 2001gd radio emission. This is similar to the case of SN 1993J where the two values were $\delta = -1.88$ and $\delta'' = -2.05$. However, it must be stated that, from pure modeling, our sparse “early” data

only constrain the values of δ and δ'' for SN 2001gd to lie between -1 and -2 . To narrow the range of these values, we have therefore assumed a value of $\delta = -1.88$ to match the value for δ determined for SN 1993J (Weiler *et al.* 2007).

The “late” period appears to be optically thin at all observed frequencies with a much steeper decline rate than is possible with the “early” data determined $\beta = -0.92$ (shown as the dashed line in Figure 1). Again, if we assume a similarity to the exponential decline seen for SN 1993J (Weiler *et al.* 2007), the late epoch of SN 2001gd is consistent with an exponential decline after day 550, with an e-folding time of 500 days. This observed “break” in the radio light curves of SN 2001gd is interpreted as indicative of a rapid transition of the blastwave into a much more tenuous medium. This occurs much earlier for SN 2001gd (day ~ 550) than that seen for SN 1993J (day $\sim 3,100$) by Weiler *et al.* (2007).

Before the break, SN 2001gd is still somewhat optically thick at 20 cm, but after the break it appears to be optically thin. This discounts the possibility of the break being the result of a sudden change in the shock velocity or magnetic field properties at the shock front since such changes would not yield an optical depth reduction. Given the similar expansion velocities of $\lesssim 19,000$ km s $^{-1}$ for SN 2001gd (derived from (Pérez-Torres *et al.* 2005); see the Introduction) and $11,000 - 15,000$ km s $^{-1}$ for SN 1993J (Marcaide *et al.* 1997; Marcaide *et al.* 2007), it is clear that both supernovae had a period of enhanced mass-loss rate preceding their explosions. Thus, assuming a blastwave velocity for SN 2001gd of $15,000$ km s $^{-1}$ and a “standard” pre-explosion wind velocity of 10 km s $^{-1}$, this enhanced mass-loss persisted for the $\sim 1,800$ years prior to the explosion. However in the case of SN 1993J, this phase began $\sim 8,800$ years earlier than the explosion of its progenitor star. The shorter duration of the high presupernova mass-loss rate for SN 2001gd is also borne out in its faster rise and higher luminosity, indicating there was less intervening, presupernova wind established, CSM to contribute to the FFA at early epochs.

4.1. The Mass-Loss Rate for the SN Progenitor

Through use of this modeling, a number of physical properties of SNe can be determined from the radio observations. One of these is the mass-loss rate from the SN progenitor prior to explosion. From the Chevalier (1982a,b) model, the turn-on of the radio emission for RSNe provides a measure of the presupernova mass-loss rate to wind velocity ratio (\dot{M}/w_{wind}) and Weiler *et al.* (1986) derived this ratio for the case of pure, thermal, external absorption by a homogeneous medium.

Given the limited amount of early radio data available for SN 2001gd, there is no need to

invoke more complex models than the simple, uniform, external thermal absorption model, so that $\tau(t = 1 \text{ day}) = K_2$ and equation (16) of Weiler *et al.* (1986) can be written:

$$\frac{\dot{M}(M_\odot \text{ yr}^{-1})}{(w_{\text{wind}}/10 \text{ km s}^{-1})} = 3.0 \times 10^{-6} \phi \tau_{\text{CSM}_{\text{homogeneous}}}^{0.5} m^{-1.5} \left(\frac{v_i}{10^4 \text{ km s}^{-1}} \right)^{1.5} \times \left(\frac{t_i}{45 \text{ days}} \right)^{1.5} \left(\frac{t}{t_i} \right)^{1.5m} \left(\frac{T}{10^4 \text{ K}} \right)^{0.68}. \quad (10)$$

Here, the extra factor ϕ is a small correction that takes into account the fact that, for SN 2001gd, the CSM density behaves like $\rho \propto r^{-1.61}$ (see below) instead of r^{-2} as it would under the usual constant mass-loss rate assumption. The factor ϕ is given by the square root of the ratio of the integration constant for τ in the case of $\rho \propto r^{-1.61}$ to the one appropriate for $\rho \propto r^{-2}$, i.e.

$$\phi = \left(\frac{2 \times 1.61 - 1}{2 \times 2 - 1} \right)^{0.5} = 0.86 \quad (11)$$

Since SN 2001gd is a Type IIb supernova as SN 1993J was, and appears to be quite similar to it, we will adopt for SN 2001gd some of the same parameters as measured for SN 1993J. Thus, for SN 2001gd we assume $v_i = 15,000 \text{ km s}^{-1}$ at $t = 45$ days, which is a value consistent with the results of Pérez-Torres *et al.* (2005) as discussed earlier.

We also adopt values of $T = 20,000 \text{ K}$, $w_{\text{wind}} = 10 \text{ km s}^{-1}$ (which is appropriate for a RSG wind), $t = (t_{6\text{cm peak}} - t_0)$ days from our best fits to the radio data, and $m = 0.845$, as measured for SN 1993J by Marcaide *et al.* (2007). With the assumptions for the blastwave and CSM properties discussed above, and the results for the best-fit parameters listed in Table 3, our estimated presupernova mass-loss rate is $\dot{M} = 5.0 \times 10^{-6} M_\odot \text{ yr}^{-1}$ at 8.6 years before explosion.

The fitting parameter value of $\delta = -1.88$ indicates that the CSM density behaves like $\rho \propto r^{-1.61}$ so that the mass-loss rate for SN 2001gd was not constant but was decreasing in the years leading up to the explosion, i.e. $\dot{M} \propto r^2 \rho w_{\text{wind}} \propto r^{0.39}$ for a constant w_{wind} .

Since the shock speed for SN 2001gd is assumed to be $\sim 15,000 \text{ km s}^{-1}$ at $t = 45$ days, but variable with time ($v \propto t^{-0.155}$ for $m = 0.845$ from Marcaide *et al.* 2007), and the pre-supernova wind velocity for an RSG is typically $\sim 10 \text{ km s}^{-1}$, we calculate that the abrupt decline in the radio light curves starting around day ~ 550 implies this change took place in the presupernova stellar wind $\sim 1,800$ years before explosion when the mass-loss rate was as high as $3.9 \times 10^{-5} M_\odot \text{ yr}^{-1}$. Integrating the mass-loss rate over the last $\sim 1,800$

years before explosion, we find that, during that time, the progenitor star shed $\sim 0.05 M_{\odot}$ in a massive stellar wind. At earlier epochs of the progenitor’s evolution the mass-loss rate was considerably lower, as indicated by the radio light curve “break” discussed above and the transition of the shock wave to a lower density CSM at that time.

5. Conclusions

Figure 1 and Table 3 show that the radio light curves for SN 2001gd can be described by standard RSN models (Weiler *et al.* 1986, 1990, 2002; Montes, Weiler, & Panagia 1997) during its “early” evolution up to day ~ 550 . After day ~ 550 the flux density decline rate clearly steepened to, in comparison with SN 1993J (Weiler *et al.* 2007), a form consistent with an exponential decay with e-folding time of 500 days. The “break” in the radio light curves for SN 2001gd is interpreted as due to a change in the average CSM density. Similar “breaks” have been identified earlier in SN 1980K (Montes *et al.* 1998), SN 1988Z (Williams *et al.* 2002), and SN 1993J (Weiler *et al.* 2007).

Normal assumptions for presupernova stellar wind properties imply a dense wind with mass-loss rate decreasing for the last $\sim 1,800$ years before explosion from $\dot{M} \sim 3.9 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$ to $\dot{M} \sim 5.0 \times 10^{-6} M_{\odot} \text{ yr}^{-1}$ around the time of explosion. The mass-loss rate was sharply lower for times earlier than $\sim 1,800$ years before explosion.

KWW wishes to thank the Office of Naval Research (ONR) for the 6.1 funding supporting his research. CJS is a Cottrell Scholar of Research Corporation and work on this project has been supported by the NASA Wisconsin Space Grant Consortium. NP is Astronomer Emeritus at the Space Telescope Science Institute (STScI) that kindly provided research facilities and partial support for this work. Additional information and data on radio supernovae can be found on <http://rsd-www.nrl.navy.mil/7213/weiler/sne-home.html> and linked pages.

REFERENCES

- Chandra, P., Ray, A., & Bhatnagar, S. 2002, IAU Circ. 7982, 2
- Chevalier, R. A. 1982a, ApJ, 259, 302
- Chevalier, R. A. 1982b, ApJ, 259, L85
- Marcaide, J. M. *et al.* 1997, ApJ, 486, L31

- Marcaide, J. M. *et al.* 2007, MNRAS, submitted
- Matheson, T., Jha, S., Challis, P., Kirshner, R., & Berlind, P. 2001, IAU Circ. 7765
- Montes, M. J., Weiler, K. W., & Panagia, N. 1997, ApJ, 488, 792
- Montes, M. J., van Dyk, S. D., Weiler, K. W., Sramek, R. A., & Panagia, N. 1998, ApJ, 506, 874
- Montes, M. J., Weiler, K. W., Van Dyk, S. D., Panagia, N., Lacey, C. K., Sramek, R. A., & Park, R. 2000, ApJ, 532, 1124
- Nakano, S., Itagaki, K., Kushida, Y., Kushida, R., & Dimai, A. 2001, IAU Circ. 7761
- Natta, A., & Panagia, N. 1984, ApJ, 287, 228
- Osterbrock, D. E. 1974, Astrophysics of Gaseous Nebulae (Freeman, San Francisco), p. 82
- Pérez-Torres, M. A., et al. 2005, MNRAS, 360, 1055
- Readhead, A. C. S. 1994, ApJ, 426, 51
- Sramek, R. A. & Weiler, K. W. 2003, Springer Lecture Notes in Physics Vol. 598: Supernovae and Gamma-Ray Bursters, 598, 137
- Stockdale, C. J., Perez-Torres, M. A., Marcaide, J. M., Sramek, R. A., Weiler, K. W., Van Dyk, S. D., Panagia, N., Lundqvist, P., Pooley, D., Immler, S., & Lewin, W. 2002, IAU Circ. 7830
- Stockdale, C. J., Weiler, K. W., Van Dyk, S. D., Montes, M. J., Panagia, N., Sramek, R. A., Perez-Torres, M. A., & Marcaide, J. M. 2003, ApJ, 592, 900
- Tully, R. B. 1988, Nearby Galaxies Catalog (Cambridge and New York: Cambridge University Press)
- Van Dyk, S., Weiler, K., Sramek, R., Rupen, M., & Panagia, N. 1994, ApJ, 432, 115
- Van Dyk, S. D., Montes, M. J., Weiler, K. W., Sramek, R. A., & Panagia, N. 1998, AJ, 115, 1103
- Weiler, K. W., Sramek, R. A., Panagia, N., van der Hulst, J. M., & Salvati, M. 1986, ApJ, 301, 790
- Weiler, K. W., Panagia, N., & Sramek, R. A. 1990, ApJ, 364, 611

- Weiler, K. W., Panagia, N., & Montes, M. 2001, *ApJ*, 562, 670
- Weiler, K. W., Panagia, N., Montes, M. J., & Sramek, R. A. 2002, *ARA&A*, 40, 387
- Weiler, K. W., Williams, C. L., Panagia, N., Stockdale, C. J., Kelley, M. T., Sramek, R. A., Van Dyk, S. D., and Marcaide, J. M. 2007, *ApJ*, submitted
- Williams, C. L., Panagia, N., Van Dyk, S. D., Lacey, C. K., Weiler, K. W., & Sramek, R. A. 2002, *ApJ*, 581, 396

Table 1. Flux Density Measurements for SN 2001gd^a

Obs. Date (UT)	Age (days)	Tel.	S (90 cm) (mJy)	S (20 cm) (mJy)	S (6 cm) (mJy)	S (3.6 cm) (mJy)	S (2 cm) (mJy)	S (1.3 cm) (mJy)
2001 Sep 03	$\equiv 0$							
2002 Feb 08	159	VLA-A	...	0.85 ± 0.15	5.05 ± 0.26	4.09 ± 0.21	...	1.37 ± 0.18
2002 Mar 02	180	VLA-A	...	1.41 ± 0.20	5.41 ± 0.28	3.73 ± 0.20	2.18 ± 0.24	1.34 ± 0.18
2002 Mar 14	192	VLA-A	...	1.84 ± 0.37	4.46 ± 0.24	...	...	...
2002 Mar 23	201	VLA-A	...	1.83 ± 0.36	...	3.66 ± 0.21	2.33 ± 0.32	1.00 ± 0.19
2002 Apr 06	215	VLA-A	...	1.99 ± 0.37	5.33 ± 0.28	3.78 ± 0.21	2.66 ± 0.30	...
2002 Jun 12	282	VLA-B	...	3.23 ± 0.37	4.84 ± 0.25	3.10 ± 0.17	...	...
2002 Jun 26 ^b	296	VLBA	...	...	...	$3.83 \pm .19$	...	...
2002 Jul 16	317	VLA-B	...	2.73 ± 0.31	4.26 ± 0.23	2.39 ± 0.14	...	...
2002 Sep 22 ^c	384	GMRT	...	3.55 ± 0.22	...	...	...	...
2002 Oct 28	421	VLA-C	...	...	...	2.07 ± 0.14	0.89 ± 0.18	0.81 ± 0.16
2002 Nov 08	432	VLA-C	...	4.22 ± 0.48	3.26 ± 0.20	...	...	...
2003 Apr 08 ^b	582	VLA-D	...	3.89 ± 0.40	1.85 ± 0.24	1.02 ± 0.05	0.63 ± 0.13	0.39 ± 0.12
2003 May 23	627	VLA-A	< 3.09	...	...	0.96 ± 0.10	...	< 0.39
2003 May 26	630	VLA-A	...	3.47 ± 0.45	1.67 ± 0.10	...	...	...
2004 Sep 10	1104	VLA-A	...	1.04 ± 0.14	...	< 0.18	< 0.79	< 0.79
2005 Jun 14	1380	VLA-C	...	< 1.12	< 0.21	< 0.14	< 0.48	< 0.42
2006 Jan 24	1605	VLA-D	...	...	< 0.39	< 0.6	...	...
2006 May 29	1729	VLA-BnA	...	< 0.32	...	...	...	...
2006 Sep 25	1849	VLA-B	...	...	< 0.29	...	...	...

^aAll upper limits are 3σ .

^bFrom Pérez-Torres *et al.* (2005); Pérez-Torres *et al.* (2005) also measured a 3σ upper limit of < 0.3 mJy for SN 2001gd on 2003 Apr 08 at 0.7 cm (43.3 GHz).

^cChandra et al. (2002)

Table 2. Flux Density Measurements for Secondary Calibrator J1310+323

Obs. Date (UT)	Age (days)	Tel. (Jy)	S (90 cm) (Jy)	S (20 cm) (Jy)	S (6 cm) (Jy)	S (3.6 cm) (Jy)	S (2 cm) (Jy)	S (1.3 cm)
2002 Feb 08	159	VLA-A	...	1.70	1.66	1.77	...	2.15
2002 Mar 02	180	VLA-A	...	1.70 ^a	1.69	1.75	2.03	2.16
2002 Mar 14	192	VLA-A	...	1.70 ^a	1.70 ^a	...	...	...
2002 Mar 23	201	VLA-A	...	1.68	...	1.80 ^a	2.08	2.32
2002 Apr 06	215	VLA-A	...	1.69	1.70 ^a	1.83 ^a	2.07	...
2002 Jun 12	282	VLA-B	...	1.67	1.73	2.01	...	...
2002 Jul 16	296	VLA-B	...	1.72	1.77	2.05	...	...
2002 Oct 28	421	VLA-C	...	...	...	2.13	2.55	2.73
2002 Nov 08	432	VLA-C	...	1.70	1.83	...	...	...
2003 Apr 08 ^b	582	VLA-D	...	1.54	1.66	...	2.40	2.91
2003 May 23	627	VLA-A	2.74	...	...	2.37	...	2.93
2003 May 26	630	VLA-A	...	1.42	1.65	...	...	...
2004 Sep 10	1104	VLA-A	...	1.14	...	2.47	2.35	2.24
2005 Jun 14	1380	VLA-C	...	1.45	1.81	1.89	1.76	1.71
2006 Jan 24	1605	VLA-D	...	...	1.44	1.35	...	...
2006 May 29	1729	VLA-BnA	...	1.58	...	...	...	...
2006 Sep 25	1849	VLA-B	...	...	2.42	...	...	...

^aValue was not measured but was interpolated from the closest calibration at that frequency.

^bFrom Pérez-Torres *et al.* (2005); Pérez-Torres *et al.* (2005) also measured a value of 2.58 Jy for J1310+323 on 2003 Apr 08 at 0.7 cm (43.3 GHz).

Table 3. Fitting Parameters for SN 2001gd

Parameter	Early (day < 550)
K_1	7.5×10^2
α	-0.94
β	-0.92
K_2	1.5×10^3
δ	-1.88
K_5	1.7×10^2
δ'	-1.5
t_0^a	2001 Sep 03
$S_{6\text{cm peak}}$ (mJy)	7.96
$L_{6\text{cm peak}}$ (erg s $^{-1}$ Hz $^{-1}$)	3.8×10^{27}
$t = (t_{6\text{ cm peak}} - t_0)$ (days)	80
\dot{M} (M_\odot yr $^{-1}$) ^b	$(0.5 - 3.9) \times 10^{-5}$
Assumed distance (Mpc)	20

^aDefined in the Introduction.

^bAssuming $w_{\text{wind}} = 10$ km s $^{-1}$, $v_i = v_{\text{blastwave}} = 15,000$ km s $^{-1}$, $T = 20,000$ K, and $t_i = 45$ days.

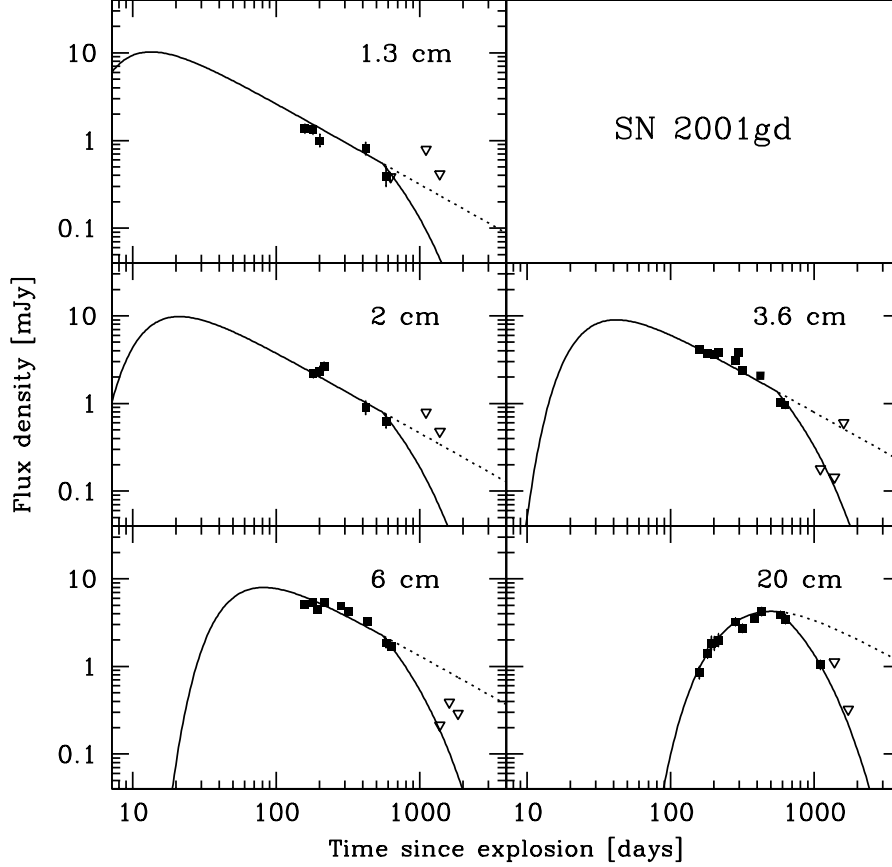


Fig. 1.— Radio “light curves” for SN 2001gd in NGC 5033. The five wavelengths, 1.3 cm (22.4 GHz; *top left*), 2 cm (14.9 GHz; *middle left*), 3.6 cm (8.4 GHz; *middle right*), 6 cm (4.9 GHz; *bottom left*), and 20 cm (1.5 GHz; *bottom right*) are shown together with their best-fit model light curves. The SN age is in days since the adopted explosion date of 2001 September 03. Because the decline index β of the radio emission steepened after day ~ 550 , following the example of SN 1993J (Weiler *et al.* 2007), we have fitted the “late” data after day 550 with an exponential decline with an e-folding time of 500 days. The inverted open triangles represent 3σ upper limits and the dotted lines show the extrapolation of the fit to the “early” data before day ~ 550 given in Table 3

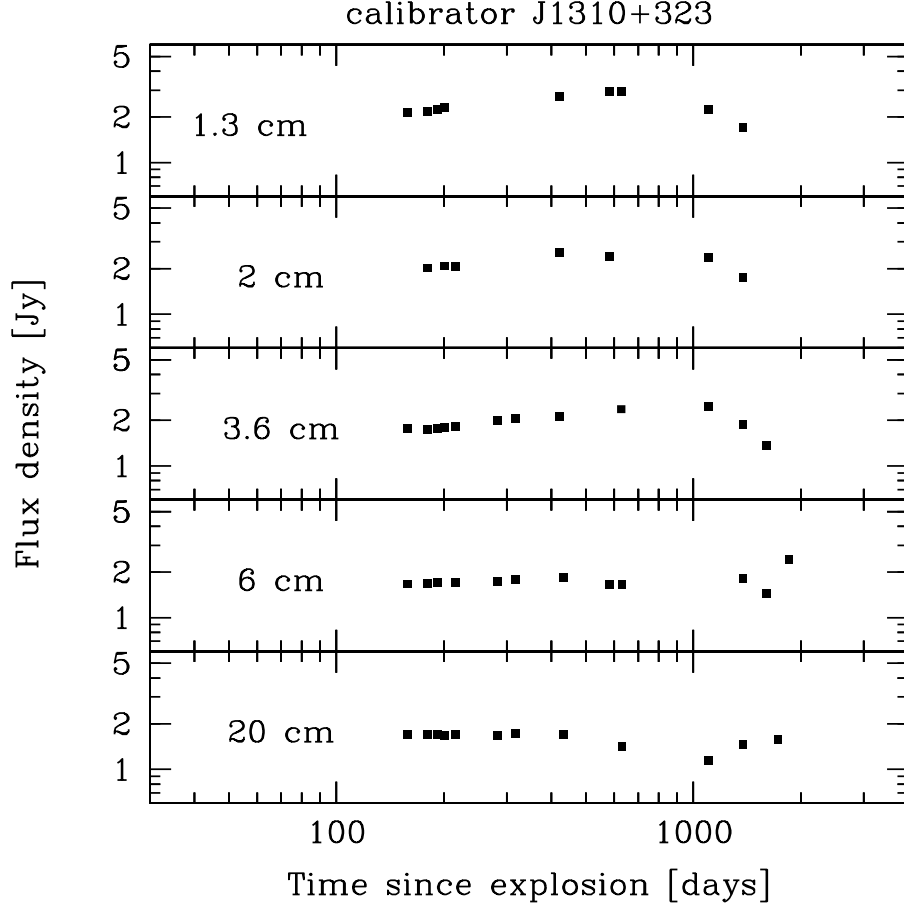


Fig. 2.— Flux density measurements of the secondary calibrator J1310+323 at the five wavelengths of 1.3 cm (22.4 GHz; *top*), 2 cm (14.9 GHz; *one below top*), 3.6 cm (8.4 GHz; *middle*), 6 cm (4.9 GHz; *one above bottom*), and 20 cm (1.5 GHz; *bottom*).